

TELEROBOTIC RESEARCH AT NASA LANGLEY RESEARCH CENTER

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ABSTRACT

The Automation Technology Branch of NASA Langley Research Center has been researching automation and robotic techniques for space operations since 1979. This branch has developed and currently maintains the Intelligent Systems Research Lab. The lab houses a collection of computers and robotic peripherals that have been organized into a simulation testbed for telerobotic research. This testbed is being used to investigate and develop techniques for telerobotic on-orbit operations, such as assembly of large space structures and servicing and repair of spacecraft.

The branch has on-going work in many areas. Manipulator research includes dual-arm coordination studies, space manipulator dynamics, end-effector controller development, automatic space structure assembly, and the development of a dual-arm master-slave telerobotic manipulator system. Sensor research includes gravity-compensated force control, real-time monovision techniques, and laser ranging. Artificial intelligence techniques are being explored for supervisory task control, collision avoidance, and connectionist system architectures. A high-fidelity dynamic simulation of robotic systems, ROBSIM, is being supported and extended. Cooperative efforts with Oak Ridge National Laboratory have verified the ability of teleoperators to perform complex structural assembly tasks, and have resulted in the definition of a new dual-arm master-slave telerobotic manipulator.

This paper presents an overview of the facilities and research thrusts of the Automation Technology Branch, and includes a bibliography of research results and technical contacts for each research area. All technical contacts named are in-house personnel of the Automation Technology Branch.

INTRODUCTION

The Automation Technology Branch of NASA Langley Research Center has been researching automation and robotic techniques for space operations

since 1979 (ref. 1). Early investigation established both the role of the branch in emphasizing the system integration aspects of telerobotics (ref. 2), and the need to provide an evolutionary development of teleoperators toward increasing levels of intelligent automation. In examining NASA mission requirements for space automation, the tasks of structural assembly and satellite servicing were chosen as research foci (ref. 3).

TELEOPERATOR AND ROBOTIC TESTBED

The Automation Technology Branch maintains the Intelligent Systems Research Lab (ISRL), which houses a collection of telerobotic subsystems organized into a modular virtual architecture (ref. 4). This architecture, designated the Teleoperator And Robotic Testbed (TART), provides an environment where teleoperator and robotic technologies may be studied at the level of abstraction that best meets the researchers' needs. TART hides many of the low-level implementation details from the user and is defined by well-documented and tightly-controlled data structures having specific access mechanisms.

TART is a layered product in which each successive layer provides additional capability to the system. Currently, five layers are implemented: (1) user, (2) system, (3) scheduling, (4) communications, and (5) servo/sensor. The lowest four layers of TART accomplish most of the detailed programming and error checking required by user applications. The technical contacts for ISRL and TART are F. Wallace Harrison and C. Henry Lenox.

TELEROBOTIC SYSTEM SIMULATION

The TART architecture has been used to develop the TeleRobotic System Simulation (TRSS), a real-time, man-in-the-loop simulation of telerobotic operations. Early TRSS studies used computer-generated graphics to investigate the effects of time delays and teleoperator control modes on a precise alignment task (ref. 5). Later studies developed efficient algorithms to handle singularities in serial link manipulators (ref. 6). These techniques were demonstrated

on the ISRL manipulators (ref. 7). Most recently, TRSS has been used to investigate telerobotic structural assembly tasks for application to Space Station construction.

Current TRSS control strategies are based on resolved motion rate control operating at 25 Hertz. Individual joint rates are integrated to provide joint positions, which are transmitted to servo-level processes resident in the manipulator controller. Operator control inputs can be referenced to arbitrary reference frames and combined with sensor-derived control signals. The technical contacts for TRSS are Donald Soloway and Bobby Glover.

Manipulator Control

A standardized set of homogeneous transform structures has been devised and implemented in TRSS to provide a generic control reference structure (ref. 8). By thus providing for the selection of arbitrary control reference frames, multiple manipulators can be simultaneously controlled individually or orchestrated to coordinate on a single task. TRSS currently incorporates two manipulators, which can cooperate in performing tasks such as positioning a long strut for connection to a node for structural assembly. The contacts for this work are Donald Soloway and L. Keith Barker.

Research continues with the Massachusetts Institute of Technology in dynamic control of manipulators in space. A virtual manipulator concept has been developed which facilitates the planning and control of the motion of manipulators mounted on spacecraft, thus minimizing the degrading consequences of manipulator/vehicle dynamic interactions (ref. 9). Additionally, the branch is supporting research in the control of flexible manipulators at the Georgia Institute of Technology. The contacts for these efforts are Jack Pennington and Donald Soloway.

An in-house effort is currently providing separate programmable controllers for each joint of the PUMA manipulators. This will allow research into alternative servocontrol strategies, including model-referenced adaptive control (ref. 10). The contact for this work is Donald Soloway.

Interest is growing in the possible use of trained neural networks to replace the need for kinematic manipulator control. Investigation is in progress of neural net capabilities and architectures. The contacts for these efforts are Donald Soloway and Nancy Sliwa.

Operator Interface

In addition to manual control, an interactive menu-driven interface is used in TRSS to provide a higher level of control abstraction to the operator, in effect automating some low-level task operations (ref. 11). This interface is organized such that more complex task operations

can be described as a script of elementary operations and invoked as a single command primitive.

As this menu interface has evolved, it has become increasingly complex. Accordingly, an effort is now underway using expert system technology to automatically generate menu scripts based on high-level task requirements. This provides the operator with increased supervisory control. The contacts for this work are Nancy Sliwa and Eric Cooper.

Sensors

Sensor-derived control signals are essential to the automation of tasks in an uncertain telerobotic environment. TRSS uses both force/torque sensing and machine vision processing to assist in controlling the manipulators. A wrist-mounted, six degree-of-freedom force/torque sensor provides force and torque data that are processed into rates. These rates are then summed into the manipulator control rates to provide compliance, obstacle avoidance, and gravity compensation for loads carried by the manipulators. Additional force/torque sensors in the end-effector have also been used for fine motion compliance in dexterous tasks. The technical contacts for this work are Donald Soloway and Marion Wise.

Vision processing in TRSS currently emphasizes the determination of position and orientation of a marked part for acquisition by the manipulators (ref. 12, 13). This is done with quadrangle projection techniques, using a minimum of four identifiable target points and the principle of perspective transformation. This allows fast, robust automatic object acquisition by the telerobot.

Elastic matching techniques are also being researched in ISRL for automatic object recognition. A linear programming method called Goal Programming has been adapted to the elastic template matching approach to pattern recognition (ref. 14). This approach has been successfully applied to 3-space location of an isolated object, shape determination of isolated planar figures, image compression/restoration, and shape decomposition.

ISRL sensing capabilities are currently being expanded to include laser ranging. With support from the National Bureau of Standards and the U.S. Army, the branch has worked with Digital Signal Corporation to produce a high-speed, extremely precise range imager for the ISRL. The concept for this imager is based on the FM radar principle which makes use of the coherence and tunability of injection laser diodes (ref. 15). Work is currently in progress for applying this technology to produce an end-effector-mounted point-ranging sensor. Contacts for vision and laser research are Plesent Goode and Karin Cornils.

End-Effectors and Tools

TRSS has been using an end-effector fabricated at Langley from designs by the University of Rhode Island (ref. 16). This end-effector, a parallel jaw gripper, has proximity and cross-fire sensors for the detection of workpieces, limit and overload sensors, and manually-exchangeable fingers (ref. 17). The Automation Technology Branch has researched several variations of this end-effector, including finger-mounted force/torque sensors, automatically exchangeable ratcheting tools, and several task-specific gripper styles.

A microprocessor controller has been developed for this end-effector, with a sophisticated monitor to examine and change gains, speeds, and sensor values, and to move the grippers. This controller has been interfaced into the TART architecture to provide automated gripping and gripper-based sensing in TRSS (ref. 18). The technical contact for this work is Marion Wise.

Collision Avoidance

The branch has supported several efforts in collision avoidance and trajectory planning, including hextree environment modelling (ref. 19), freeway trajectories (ref. 20), gaussian configuration spaces (ref. 21), and dual-arm collision avoidance using velocity constraints (ref. 22). Research is currently in progress in-house establishing collision avoidance criteria for telerobotic environments, and developing a real-time collision avoidance monitor using abstract geometry and lazy evaluation techniques to avoid unnecessary calculations. The technical contact for this work is Nancy Sliwa.

System Architecture

In addition to the continuing enhancement of the TART virtual architecture, in-house research is continuing in the use of behavioral networks as a control architecture for telerobotic systems. Behavioral nets, a variant of connectionism, could provide a unified approach to combining high-level intelligent task control with low-level sensor and actuator control (ref. 23). This structure is also being investigated for use in interactive dynamic planning and scheduling systems. The contact for this work is Nancy Sliwa.

ROBOT SIMULATION

The Automation Technology Branch supported the development of ROBSIM (ROBot SIMulation), a high-fidelity, dynamic, off-line design and analysis tool for robotic systems and environments (ref. 24). This product, originally developed by Martin-Marietta, is being extended and enhanced by both in-house personnel and Grumman contractors. A real-time 3-D graphics display, improved user input interface, and interfaces to collision detection algorithms are upgrades which are currently in progress. This

product has been distributed to more than 20 universities and research groups. The contacts for this work are F. Wallace Harrison and William Doggett.

TELEOPERATOR PERFORMANCE VERIFICATION

Teleoperated systems have so far seen only limited commitment for use in space due to the uncertainty of such systems' capabilities to perform complex realistic space tasks and of the time required to accomplish such tasks. The Automation Technology Branch, in cooperation with Oak Ridge National Laboratory (ORNL), has attempted to demonstrate the feasibility of teleoperated space operations and has established a database of task completion times (ref. 25).

Assembly Concept for Construction of Erectable Space Structures (ACCESS I) was a structural assembly flight experiment intended to study and verify the ability of astronauts to assemble in space a repetitive truss structure typical of that proposed for Space Station. Using the master-slave dual-arm manipulator (M-2) and highly skilled operators at ORNL, the ACCESS I experiment was duplicated in a controlled environment. This experiment proved that teleoperators have sufficient dexterity and control to perform such tasks in a timely manner without damage to the task components or to the manipulator system. Potential hardware modifications have been identified, and a data base of performance metrics has been established. The contacts for this work are Walter Hankins and Randolph Mixon.

SPACE STRUCTURE ASSEMBLY SIMULATION AND LAB

In cooperation with the Langley Structures Directorate, the Automation Technology Branch is investigating the automated assembly of large tetrahedral truss structures, such as would be used for large space antennae. Branch researchers have developed a real-time, 3-D perspective graphics simulation to be used in configuration analysis and development of assembly techniques. Since this analysis requires manual input, necessary components of the simulation include a command interpreter, a truss naming convention, a robotic system knowledge base, and an automated assembly sequence based on simple common substructures. Simple rules have been developed to allow an untrained operator to understand the assembly sequence and to successfully intervene in the event of system problems. An expert system approach is being investigated to minimize truss structure moves, potential interference, and robot arm base moves. The contacts for this work are Ralph Will and Sixto Vasquez.

The Automation Technology Branch and the Langley Structures Directorate have initiated the development of a laboratory facility to verify and demonstrate this approach to telerobotic construction of large space structures. The objective of this research is to design and test

structural elements, fasteners, end effectors, and tooling for telerobotic assembly of space structures, and to develop design criteria for manipulators, sensors, computers, and human/machine interface for systems for large space assembly. Future research with this facility will include enhanced sensing capability, curved structure assembly, repair of damaged structure components, and the automation of additional construction tasks, such as cabling and panel installation. Contacts for this work are Marion Wise and Jack Pennington.

SPACE MANIPULATOR DEVELOPMENT

The Automation Technology Branch is working with Oak Ridge National Laboratory (ORNL) in developing a new concept in telerobotic manipulators (ref. 26). The Laboratory Telerobotic Manipulator (LTM) design combines the best capabilities of teleoperated manipulators and robotic manipulators. The objectives of the LTM program are:

1. Provide prototypical laboratory hardware for NASA ground-based research in shared teleoperator/autonomous control, teleoperator control methods, and space task demonstrations.
2. Provide a high quality, dexterous, dual-arm, force-reflecting teleoperator to maximize the commonality to astronaut EVA task performance.
3. Provide robotic features for laboratory research and an evolutionary path toward system autonomy.
4. Provide configuration and performance consistent with a space flight system.

Unique features of the LTM include (1) replicated joint concept for reduced design and fabrication cost, (2) dual-arm system for two-handed tasks and tooling, (3) differential traction drive mechanism for low backlash and high efficiency, (4) redundant kinematics for singularity and obstacle avoidance, (5) an interface to the GSFC/JPL Smart End-Effector, and (6) a hierarchical, distributed digital control system, with graphics-oriented operator interface.

LTM is configured as a dual-arm master-slave system. Each seven-degree-of-freedom arm has pitch and yaw motions in the shoulder, elbow, and wrist, plus roll motion at the wrist. Two basic two-axis modules provide speed and torque options, and are used in both the master and slave arms.

The LTM control architecture supports both robotic and teleoperated operations with real-time human control. The system will be entirely digital, using 32-bit microprocessors, standardized bus structures, and software implemented in

high-level languages such as C, Pascal, Fortran, and Fortran.

Detail design and fabrication of the first prototype of this space telerobotic system has begun, with initial operational planned for mid-1988. The Langley contacts for this work are Alfred Meintel and Jack Pennington.

INTERCENTER COOPERATIVE EFFORTS

Members of the Automation Technology Branch serve as consultants for and participants in several NASA automation and robotic efforts. These efforts include the Mars Rover project, the Flight Telerobotic Servicer project, the Telerobotic Demonstration Program, and the Systems Autonomy Technology Program. All branch publications are available upon request.

CONCLUSION

The Automation Technology Branch has developed an excellent telerobotic system research facility and maintains a group of in-house researchers who are competent not only in tele-robot component technology, but also in the integration of such technology into specific application systems. While pursuing independent research to extend the state of the art in telerobotics for space applications, the branch is also cooperating with other research groups to solve specific application problems, advancing the use of telerobotics to fulfill NASA mission objectives.

REFERENCES

1. Meintel, Alfred and Larsen, Ron, "NASA Research in Teleoperation and Robotics," Society of Photo-Optical Instrumentation Engineers Conference, San Diego, California, August 1982.
2. Harrison, F. Wallace and Orlando, Nancy, "System-Level Approach to Automation," Fourth Annual UAH/UAB Robotics Conference, Huntsville, Alabama, April 1984.
3. Meintel, Alfred and Schappell, Roger, "Remote Orbital Servicing System Concept," Vol. 2, Satellite Services Workshop, NASA Johnson Space Center, Houston, Texas, June 1982.
4. Harrison, F. Wallace and Pennington, Jack, "System Architecture for Telerobotic Servicing and Assembly Tasks," 1986 SPIE Cambridge Symposium on Optical and Optoelectric Engineering, Cambridge, Massachusetts, October 1986.
5. Pennington, Jack, "A Rate Controlled Teleoperator Task with Simulated Time Delays," TM-85653, NASA Langley Research Center, September 1983.

6. Barker, L. Keith, Houck, Jacob and Carzoo, Susan, "Kinematic Rate Control of Simulated Robot Hand at or Near Wrist Singularity," TP-2240, NASA Langley Research Center, May 1984.
7. Hankins, Walter and Mixon, Randy, "Baseline Experiments in Teleoperator Control," TP-2547, NASA Langley Research Center, July 1986.
8. Barker, L. Keith and Soloway, Donald, "Coordination of Multiple Robot Arms," JPL Workshop on Space Telerobotics, Pasadena, California, January 1987.
9. Dubowsky, Steven, and Vafa, Zia, "A Virtual Manipulator Model for Space Robotic Systems," JPL Workshop on Space Telerobotics, Pasadena, California, January 1987.
10. Kornbluh, Roy, "An Experimental Evaluation of Robotic Manipulator Dynamic Performance Under Model Referenced Adaptive Control," Master's Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, September 1984.
11. Cooper, Eric and Sliwa, Nancy, "ISRL TRSS Operator Menu Interface," ATB internal documentation, NASA Langley Research Center, 1987.
12. Goode, Plesent and Cornils, Karin, "Monovision Techniques for Telerobots," JPL Workshop on Space Telerobotics, Pasadena, California, January 1987.
13. Cornils, Karin and Goode, Plesent, "Location of Planar Targets in Three Space From Monocular Images," 1987 Goddard Conference on Space Applications of Artificial Intelligence and Robotics, Greenbelt, Maryland, May 1987.
14. Goode, Plesent, and Cornils, Karin, "A Multifunction Recognition Operator for Telerobotic Vision," AIAA Guidance, Navigation, and Control Conference, Williamsburg, Virginia, August 1986.
15. Goodwin, F., "Coherent Laser Radar 3-D Vision Sensor," Sensors '85, Detroit, Michigan, November 1985.
16. Tella, R., Birk, J. and Kelly, R., "General Purpose Hands for Bin-Picking Robots," Man and Cybernetics, Vol. SMC-12, No. 6, November/December 1982.
17. Wise, Marion, "ISRL Parallel Jaw Gripper End-Effector," ATB internal documentation, NASA Langley Research Center, 1984.
18. Bynum, Dr. Wm., "Command/Response Protocols and Concurrent Software - Final Report," NAG-1-670, NASA Langley Research Center, June 1987.
19. Potter, Dr. Jerry, "Robot Environment Expert System," CR-3915, NASA Langley Research Center, August 1985.
20. Brooks, Dr. Rodney, "Find-Path for a PUMA-Class Robot," Third Annual National Conference on Artificial Intelligence, Washington, D.C., August 1983.
21. Krause, Donald, "Path Planning with Obstacle Avoidance," NAG-1-632, NASA Langley Research Center, January 1987.
22. Wallace, Richard, "Three Findpath Problems," Fourth Annual National Conference on Artificial Intelligence, Austin, Texas, August 1984.
23. Sliwa, Nancy and Soloway, Donald, "A Lattice Controller for Telerobotic Systems," American Controls Conference, Minneapolis, Minnesota, June 1987.
24. Lowrie, James et al., "Evaluation of Automated Decisionmaking Methodologies and Development of an Integrated Robotic System Simulation," CR-165975, NASA Langley Research Center, September 1982.
25. Hankins, Walter, Mixon, Randolph, Jones, Howard, and Burgess, Thomas, "Space Truss Assembly Using Teleoperated Manipulators," 1987 Goddard Conference on Space Applications of Artificial Intelligence and Robotics, Greenbelt, Maryland, May 1987.
26. Herndon, J., Hamel, W. and Kuban, D., "Traction-Drive Telerobot for Space Manipulation," 1987 IEEE International Conference on Robotics and Automation, Raleigh, North Carolina, April 1987.